CHAPTER 2 MAGNETIC LEVITATION TO CREATE REDUCED GRAVITY ENVIRONMENTS

Magnetic Levitation for Exploration

by Bob Silberg, Raytheon

A session on magnetic levitation began with a report by Jim Valles of Brown University on simulation of Martian and Lunar gravity. A magnetic ground-based device would be extremely helpful to studies of the impact reduced gravity has on living things, and the effort to mitigate any harmful effects. The ability to simulate microgravity on the ground would also be extremely useful as a substitute for the ISS, enabling investigations formerly planned for that facility to be carried out on Earth. Valles emphasized the cost-effectiveness of the project compared to experiments in space that use rotation to introduce a controlled level of gravity. In addition, he pointed out that magnetic levitation on Earth has the advantage of long experimental times with a controlled laboratory environment.

Charles Rosenblatt of Case Western Reserve University spoke on temporal measurements of surfactant squeeze-out from a surface, using magnetically-levitated liquid bridges. He said that magnetic levitation has numerous applications in studies of fluids, "soft" and "hard" condensed matter physics, and biophysics, and spoke of its application for soil wetting in future Martian agriculture. Rosenblatt pointed out that magnetic levitation makes it possible to adjust gravity to any desired value.

Yuanming Liu of the Jet Propulsion Laboratory discussed JPL's magnetic low-gravity simulator. He said the group has been able to levitate liquid helium, a difficult substance to levitate. For exploration-related study of fluid systems, he said JPL proposes to construct a new facility using a large-bore (~3-inch) superconducting magnet in a superfluid dewar.

Magnetic Levitation Based Martian and Lunar Gravity Simulator

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Missions to Mars will subject living specimens to a range of low gravity environments. Deleterious biological effects of prolonged exposure to Martian gravity (0.38 g), Lunar gravity (0.17 g), and microgravity are expected, but the mechanisms involved and potential for remedies are unknown. We are proposing the development of a facility that provides a simulated Martian and Lunar gravity environment for experiments on biological systems in a well controlled laboratory setting. The magnetic adjustable gravity simulator (MAGS) will employ intense, inhomogeneous magnetic fields to exert magnetic body forces that oppose the body force of gravity on a specimen. By adjusting the magnetic field, it is possible to continuously vary (increase or reduce) the total body force acting on a specimen. This technique has been used to levitate a range of organisms in ground-based experiments. The simulator system considered here will consist of a superconducting solenoid with a room temperature bore that such that the available sample space will be sufficient to accommodate small whole organisms, cell cultures, and gravity sensitive bio-molecular solutions. It will have good optical access so that the organisms can be viewed in situ. This facility will be valuable for experimental observations and public demonstrations of systems in simulated reduced gravity.

Magnetic Field Gradient Levitation System for Physics and Biophysics

Brown University

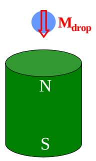
J. M. Valles, Jr., Brown University, Department of Physics

WHY AND WHAT?

We are developing a Magnetic Field Gradient Levitation (MFGL) apparatus as a ground based system that can simulate a low gravity environment for the study of physics and biophysics in diamagnetic systems. MFGL is being applied successfully in studies of fundamental physics in superfluid helium and is testing potential superfluid helium experiments for space flight. Other organic physical and biological systems, which have been or are potentially interesting to study in the microgravity environment of space do not function at cryogenic temperatures. The goal of our work is to extend the use of MFGL to such systems.

How it works:

Water Droplet (χ_ρ):



Force per gram:

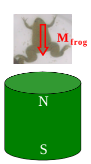
$$f = -g + \frac{\chi_\rho}{2}\frac{dB^2}{dz}$$

Levitates:

$$B\frac{dB}{dz} = -\frac{g}{\chi_\rho} = \text{-13.6}\,\frac{\text{T}^2}{\text{cm}}$$

where g is the acceleration due to gravity, χ_ρ is the specific susceptibility, B is the magnetic field and z is the coordinate parallel to **g**. In the levitated state, all gravitationally induced stresses are absent because the magnetic force exactly cancels the gravitational force on each molecule exactly.

For a heterogeneous substance the cancellation is not perfect and gravitationally induced stresses remain. For example:



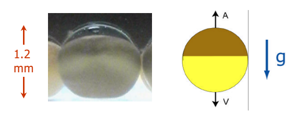
- Frog=water+protein+lipid *with different* χ*'s*
- Levitation for: $\frac{\langle \chi_\rho \rangle}{2}\frac{dB^2}{dz} = g$

Thus, MFGL does its best at removing gravitational stresses if $\chi_{\rho i} \approx \langle \chi_\rho \rangle$, where $\chi_{\rho i}$ is the specific susceptibility of the i^{th} substance.

PREVIOUS WORK

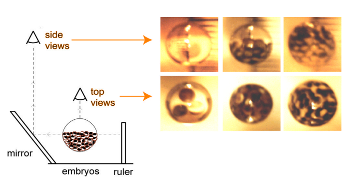
In earlier work, we demonstrated the feasibility of MFGL as a low gravity simulation technique using embryos of the frog *Xenopus laevis* as the system. We chose frog embryos for preliminary experiments because previous investigations suggested that magnetic fields as large as 7 Tesla do not adversely affect their development and because their early development exhibits well characterized sensitivity to gravity as shown by ground based and space based investigations.

XENOPUS LAEVIS PICTURE AND SKETCH



Below is a schematic of the experimental setup and pictures of droplets of buffered saline solution containing different volume fractions of fertilized frog eggs stably levitated in the bore of a Bitter solenoid at the Francis Bitter National Magnet Laboratory.

Images of Levitating Embryos



The 8mm diameter droplets assume a spherical shape indicating that gravitational stresses on them have been reduced below the strength of surface tension effects. Levitation of a pure droplet occurs at a magnetic field/field gradient product of 13.7 T^2/cm. The embryos reside at the bottom of the droplet (see Figs. c and e) indicating that the saline experiences a net body force up and the embryos experience a net body force down.

Material	$-\chi_\rho \times 10^6$ (cm³/g)	Density (g/cm³)	Volume Fraction (%)	Mass Fraction (%)	$\frac{g_{lev,i}}{g}$
Double Distilled	0.720*	1.00	---	---	---
Buffered Saline	0.720	1.01	---	---	---
Embryos+	0.690	1.09	96	95	<0.003
Pellet fraction	0.638	1.18	29	32	0.075
Cytosolic fraction	0.703	1.03	66	64	-0.02
Lipid fraction	0.646	0.85	5	4	0.06

Table 1: Properties of embryo constituents

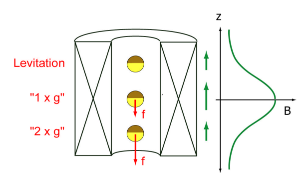
PROMISING!

The body forces on the constituents of the embryos are reduced significantly in the levitated state.

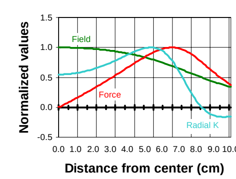
THE SYSTEM

A superconducting solenoid with a room temperature bore that generates a magnetic force strong enough to levitate or cancel the effects of gravity in common organic materials (e.g. water, proteins, polypropylene, etc.) has been designed with American Magnetics Inc. The system fits in a standard laboratory space. This feature and the fact that the field can be on indefinitely makes it possible to subject experimental systems to a well controlled, altered gravity environment for periods of time that can extend as long as a space shuttle flight. Thus, it can be conducive for pre-space flight studies of the sources of gravitational sensitivity in biological systems and for the investigation of soft condensed matter systems in the virtual absence of gravity.

Schematic of the Solenoid



Solenoid Specifications



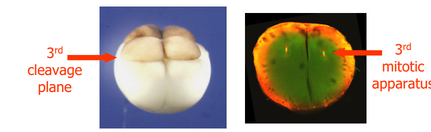
Room T Bore Diameter	25 mm
Maximum Force	1630 T^2/m
Force Homogeneity	2% in >1 cm^3
Minimum χ_ρ for levitation	$-.63\times10^{-6}$ cm^3/g
Central Field (max.)	14.9 T

Equipment will be developed for imaging and recording the motion and changes in samples *in situ.*

FIRST APPLICATIONS

Our initial plans are to perform experiments on two biological systems, embryos of the frog *Xenopus laevis* and *Paramecium biaurelia*, that have shown well-defined gravitational sensitivity in experiments on the Space Shuttle.

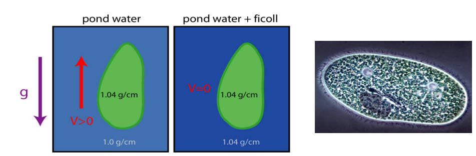
Xenopus laevis eggs



Eggs raised in microgravity or raised on a clinostat, exhibit a 1) lower third cleavage plane (see above), 2) 2 to 3 cell thicker blastocoel roof and 3) exhibit blastopore lip formation closer to the vegetal pole. We will examine how MFGL influences each of these features. In particular, we will use immunocytochemistry and confocal microscopy on MFGL eggs to image how the mitotic apparatus position, which determines the cleavage plane position, changes.

Paramecium biaurelia

These single cell organisms exhibit positive gravitactic behavior, i.e. they swim against gravity. They are 250 μm in length and 50 μm in diameter. Since they are 4% more dense than water they sediment if they do not swim.



Placing the paramecium in a medium (e.g. a ficoll solution, see above) or putting them in a low gravity environment (e.g. space) eliminates the gravitactic behavior (Hemmersbach et al.). The mechanisms involved are incompletely understood.

Field×Field Gradient (kG^2/cm)	Relative Buoyancy for Paramecium in Water	Relative Buoyancy for Paramecium in a 7% Ficoll Solution
1600	1.52	1.70
1200	1.39	1.27
800	1.26	0.85
400	1.13	0.42
0	1.00	0.00
-400	0.87	-0.42
-800	0.74	-0.85
-1200	0.61	-1.27
-1600	0.48	-1.70

Using the MFGL apparatus and different density media for the paramecium we can vary the buoyant force in novel ways. The table above shows conditions under which we can vary the buoyant force on the paramecium by more than a factor of three by moving them through different regions in solenoid.

Measurements of Surfactant Squeeze-out Using Magnetically-Levitated Liquid Bridges

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Department of Physics
Case Western Reserve University

Work published in **Colloids and Surfaces A** ***218*****, 65 (2003)**

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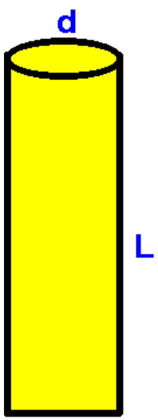
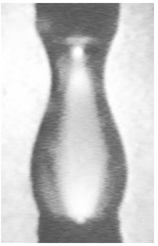
Liquid Bridges

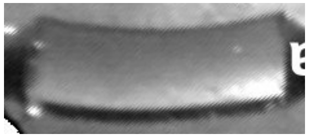
- Liquid bridges: Columns of liquid supported by two solid surfaces — These are generally opposing right circular cylinders in 0g.



- For a *cylindrical* bridge of length *L* and diameter *d*, in zero g, the maximum slenderness ratio Λ [L/d] = π [Rayleigh]

- In the presence of gravity the cylindrical shape of an axisymmetric bridge tends to deform (see our work **J. Coll. Int. Sci.** ***213*****, 592 (1999)**)





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Principles of magnetic levitation
(see our work in **Phys. Fluids 10, 2208 (1998)**)

- Fluid has a volumetric magnetic susceptibility χ. On applying field H:
- Energy per unit volume is $U = -\frac{1}{2}\chi H^2$ ➔
- **Force per unit volume is $F = -\nabla U = \frac{1}{2}\chi\nabla H^2 = \chi H\nabla H$. This force can be oriented to counteract gravity.**
- Dissolve paramagnetic manganese chloride tetrahydrate in water or glycerol to create highly paramagnetic fluid that can be controlled with a relatively small field.

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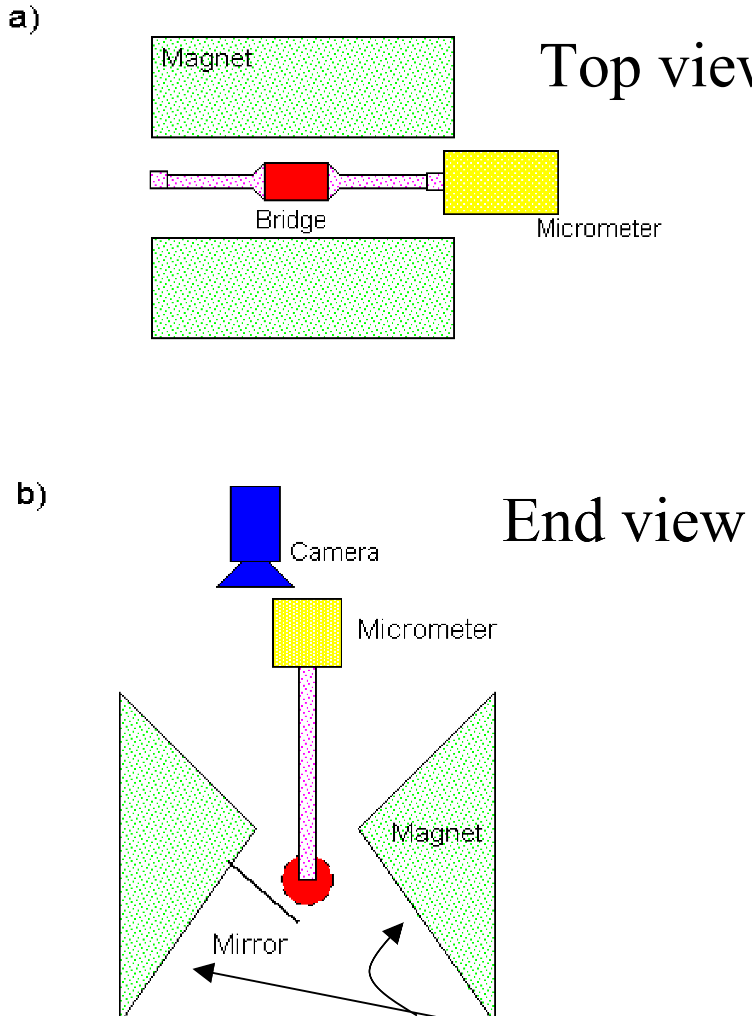
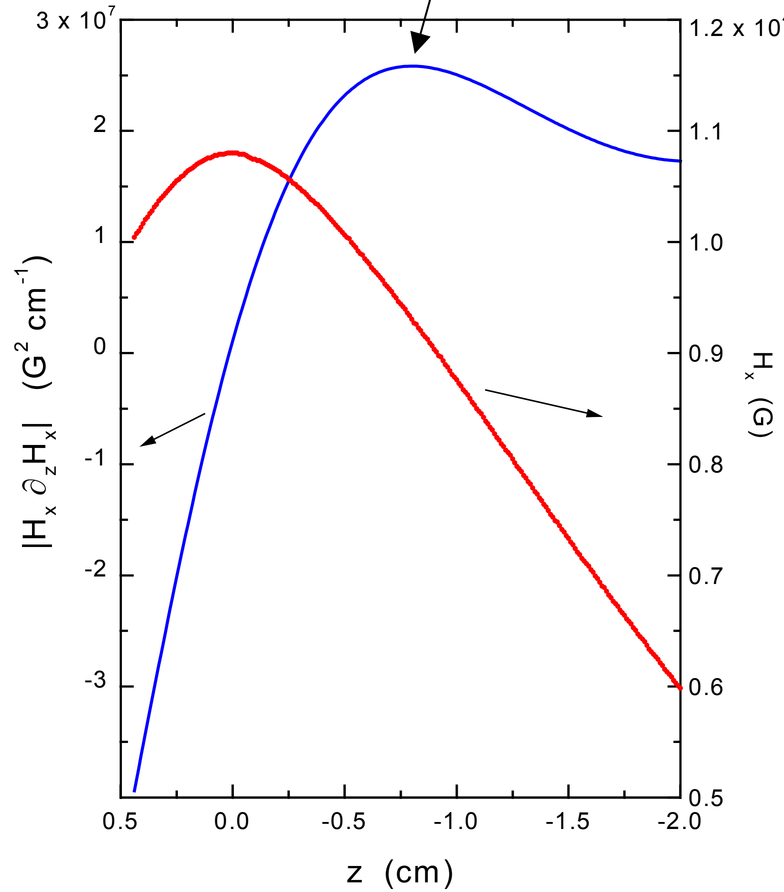
Thus the effective body force on the column may be controlled by varying the current in the magnet — as a function of time!

Apparatus



Region of quasi-uniform force



H and H∇H profiles

"Faraday pole pieces" create uniform *force*

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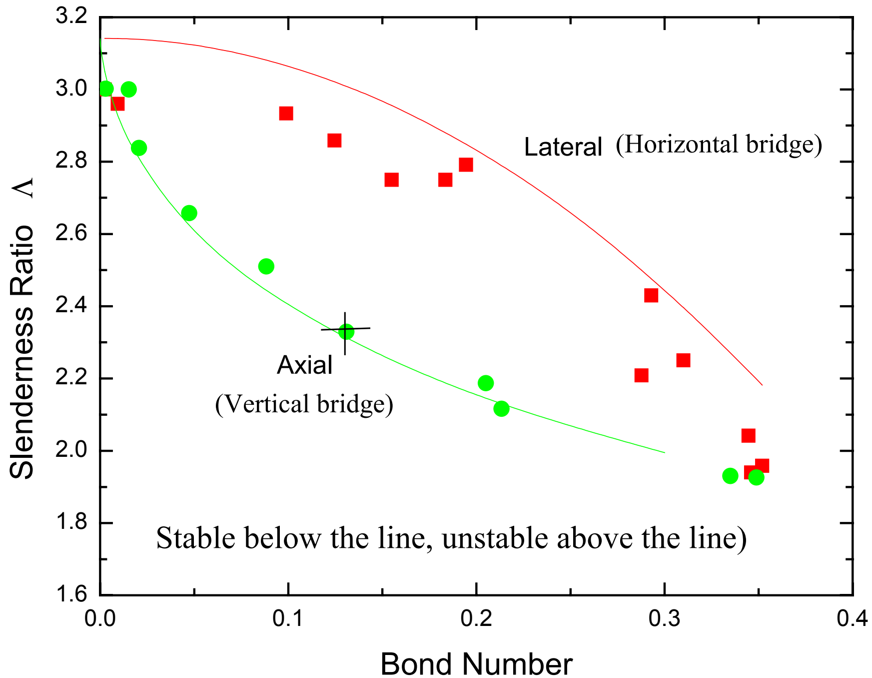
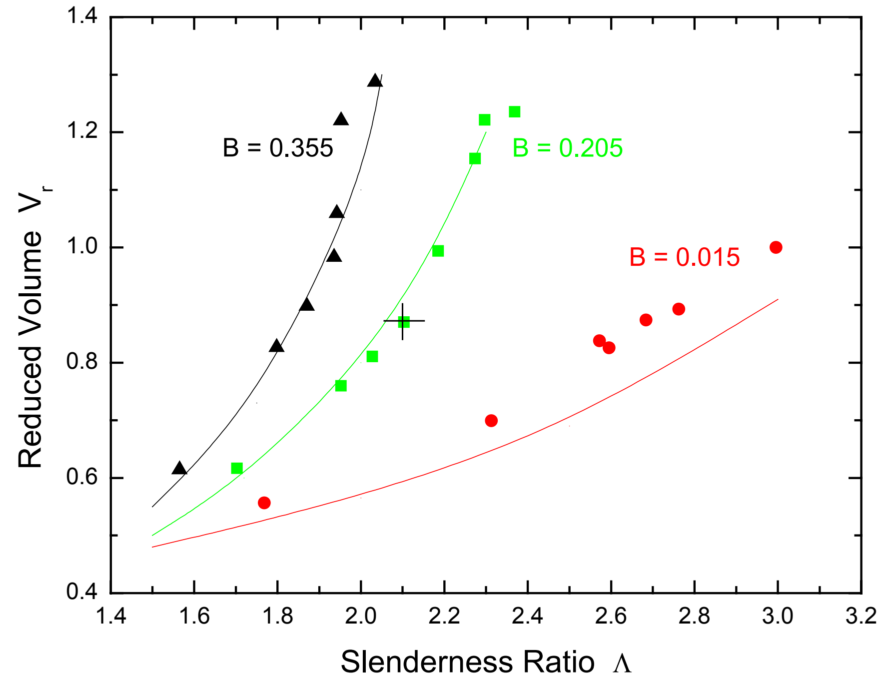
We have looked at stability issues





Stability of cylindrical bridges (V_r=1) vs. Bond number

Stability curves as function of V_r at fixed Bond number(s)

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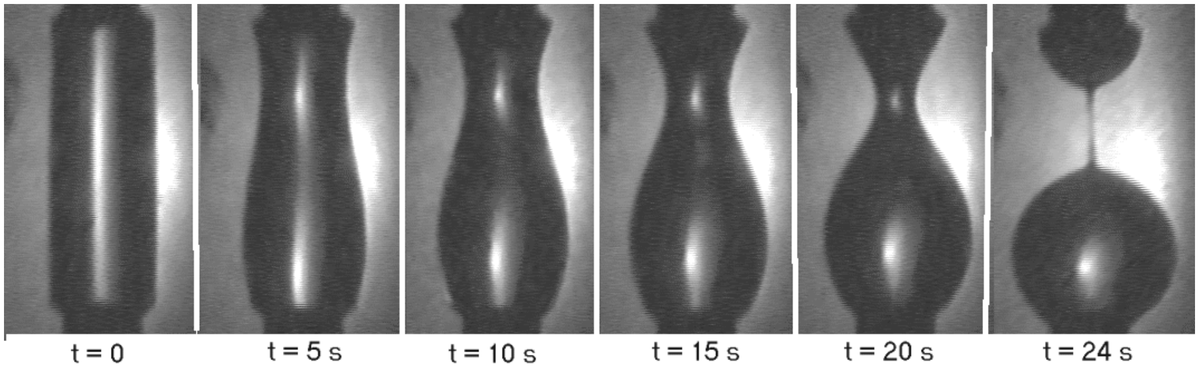
Bond number: $$B \equiv \frac{\left(\rho g - \frac{1}{2}\chi \nabla H^2\right) d^2}{4\sigma}$$

Ratio of gravitational force to surface forces

We have looked at collapse dynamics

Glycerol + manganese chloride tetrahydrate



Sequence of images of a glycerol bridge after the upward magnetic force is reduced suddenly. Bridge collapses over time due to gravity. t corresponds to time, in seconds

Movie may be viewed at

http://liq-xtal.case.edu/Videos.htm

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We have looked at resonance behavior

Vary the total body force sinusoidally at frequency ω and examine the response.

First, set *time averaged* Bond number B^o_{eff} by applying appropriate d.c. current i_o, and therefore $H\nabla H$.......

Then, modulate magnet current.

Force $\propto (i_o + \delta i \sin \omega t)^2$, and

$\delta B_{eff} \propto 2 i_o\, \delta i \times \sin \omega t\ + O(\delta i^2) \sin^2 2\omega t$

Movie may be viewed at

http://liq-xtal.case.edu/Videos.htm

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Dynamic surface tension

The change of surface tension with time as surfactant molecules move between the surface and bulk

Motivation: Investigate "respiratory distress syndrome" in neonates.

- During respiration alveoli to grow and shrink periodically
- This requires *dynamic* variation of surface tension to balance $\Delta P = \dfrac{2\sigma}{R}$
- Premature infants have not manufactured sufficient surfactant (e.g., phosphatidylcholine). Thus their pulmonary fluid cannot respond properly during breathing.

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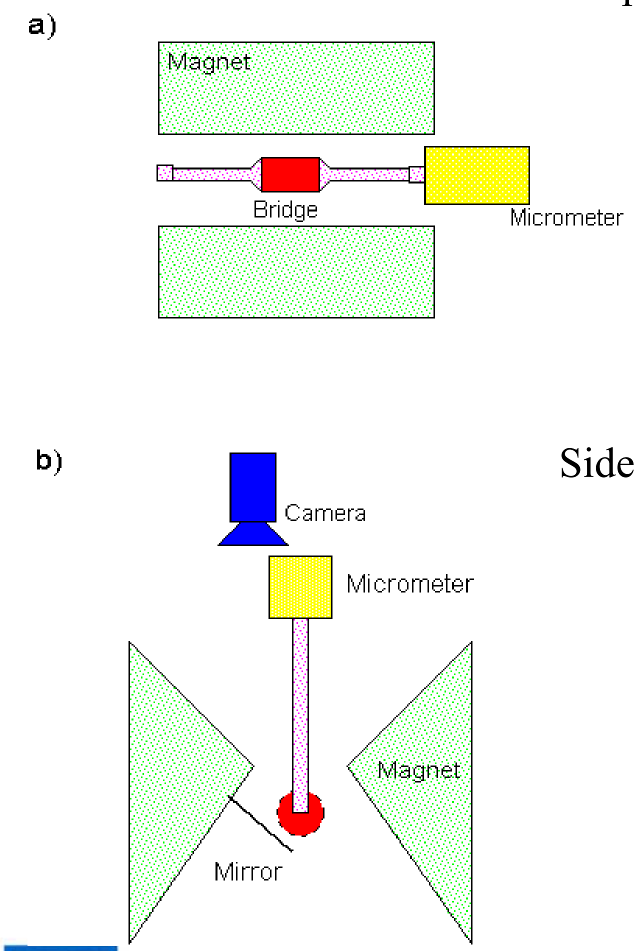
Use horizontal bridge to determine "squeeze-out time" of surfactant from surface.

Top View



Side View

As a function of surfactant concentration:

Rapidly reduce bridge length in zero gravity

Examine the ***electrical resistance vs. time*** of the bridge when the lateral area of the bridge is reduced suddenly. (In zero effective gravity the only relevant force is surface tension)

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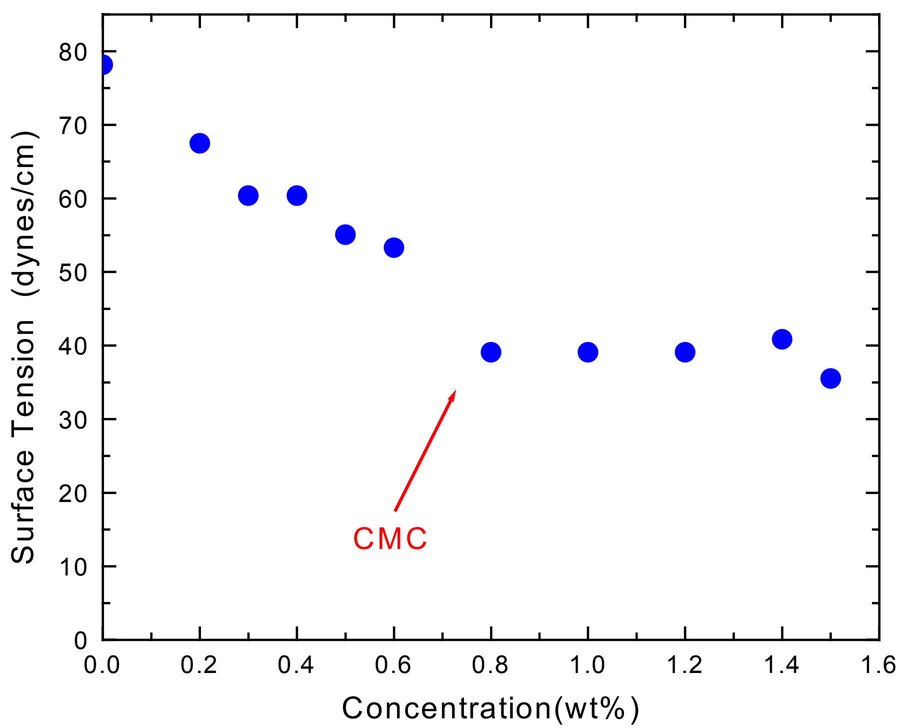
- Mixtures of paramagnetic liquid ($MnCl_2 \cdot 4H_2O$/Water)
- Add Dodecyl trimethyl ammonium chloride (cationic surfactant)

  $0 \leq X \leq 1.5$ wt. %.

- Critical Micelle Concentration (CMC) is determined from surface tension measurements using capillary rise technique. (Above CMC additional molecules tend to form micelles rather than adsorb at the surface)



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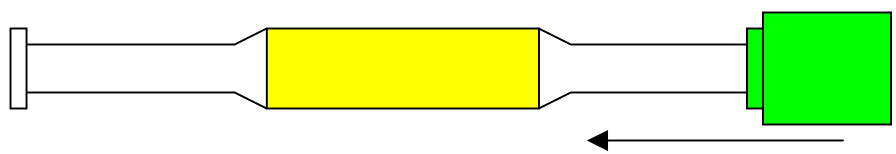
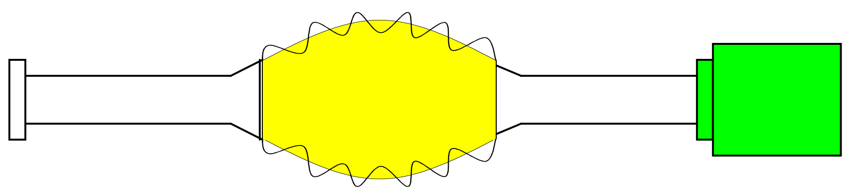
- For each concentration X of surfactant, bridges of $\Lambda = 2.5$ are created.

- A rapid change of length (1.3 mm in 500 ms) forces it to assume a new shape.

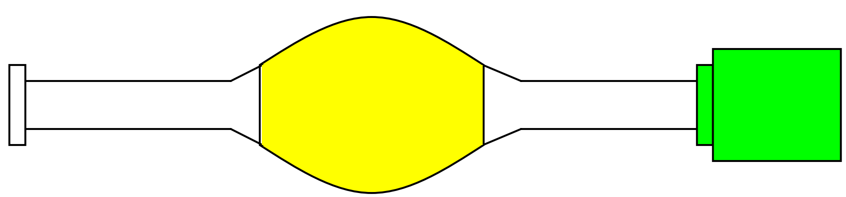


Movement of support rod



Instantaneous shape

There is a transient buckling of the surface after the bridge is “squished” in order to accommodate the surfactant that has not yet gone from the surface into the bulk. As surfactant is squeezed-out into bulk, the surface area of the bridge is reduced to the final equilibrium shape



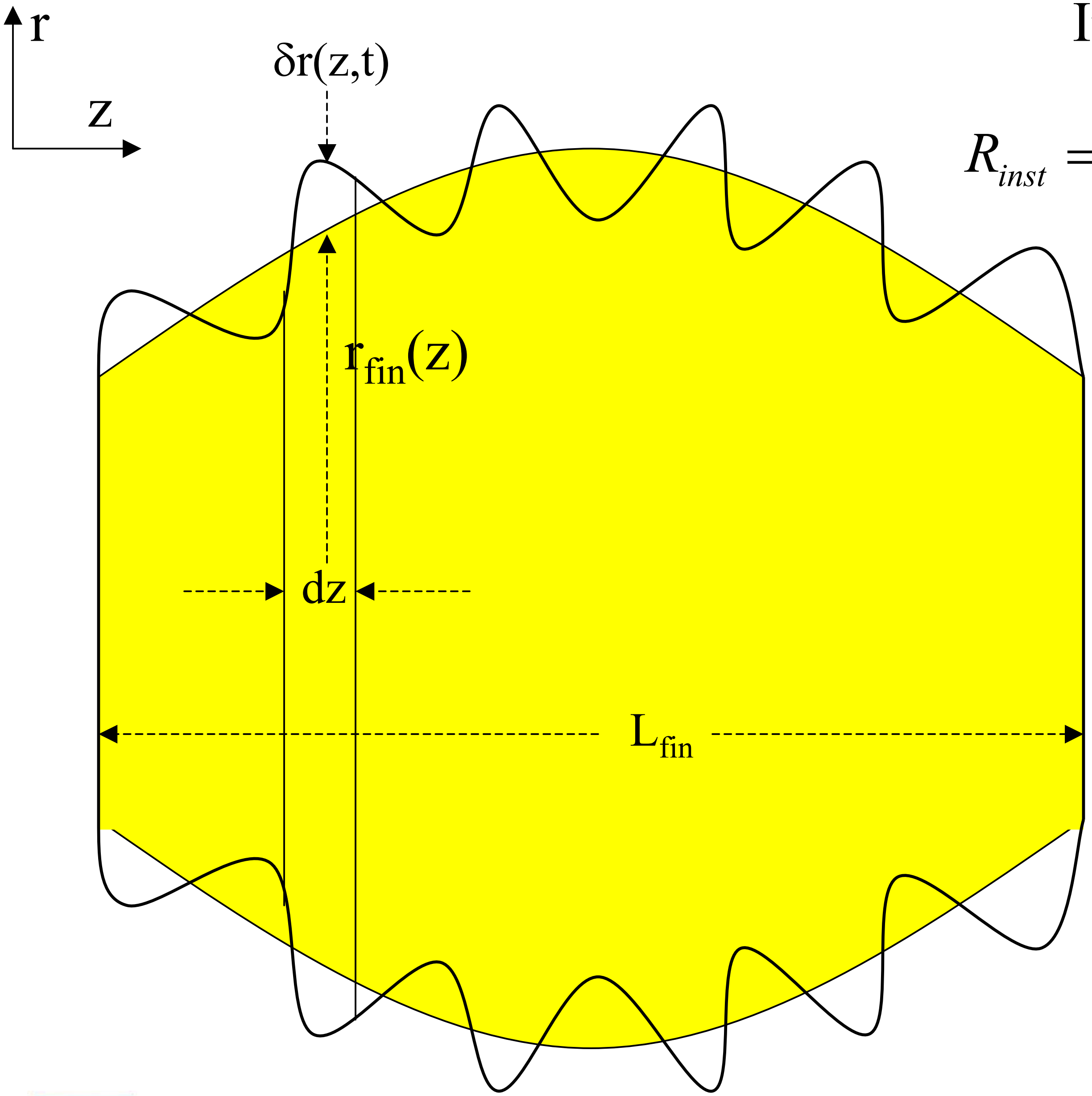
Final shape as $t \rightarrow \infty$

Crenellations are due to:

- Induced capillary waves during "squishing"
- Accommodation of surfactant that cannot be squeezed out from surface instantaneously when the bridge area is reduced during "squishing"

The relaxation time of the crenellations for large X is related to the squeeze-out time of the surfactant, and therefore to the response time of the (dynamic) surface tension.

This relaxation time is determined experimentally by the relaxation of electrical resistance across the bridge $R = \rho L/A$



Instantaneous resistance:

$$R_{inst} = \int_{z=0}^{L_{fin}} \frac{\rho}{\pi\left[r_{fin}(z) + \delta r(z,t)\right]^2} dz$$

Final resistance:

$$R_{fin} = \int_{z=0}^{L_{fin}} \frac{\rho}{\pi r_{fin}^2(z)} dz$$

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We can see that $R_{inst} > R_{fin}$:

Expand R_{inst} in powers of $\delta r(z,t)$, from which

$$R_{inst} = \int_{z=0}^{L_{fin}} \frac{\rho dz}{\pi r_{fin}^2(z)} + \int_{z=0}^{L_{fin}} \frac{\rho}{\pi r_{fin}^2(z)} \left[-2\frac{\delta r(z,t)}{r_{fin}(z)} + 3\left(\frac{\delta r(z,t)}{r_{fin}(z)}\right)^2 + \right. \\ \left. -4\left(\frac{\delta r(z,t)}{r_{fin}(z)}\right)^3 + 5\left(\frac{\delta r(z,t)}{r_{fin}(z)}\right)^4 - + \ldots \right] dz$$

1. Even order terms all have positive coefficients
2. From volume conservation, local negative $\delta r(z)$ terms are larger than local positive $\delta r(z)$ terms

$\rightarrow R_{inst} > R_{fin}$

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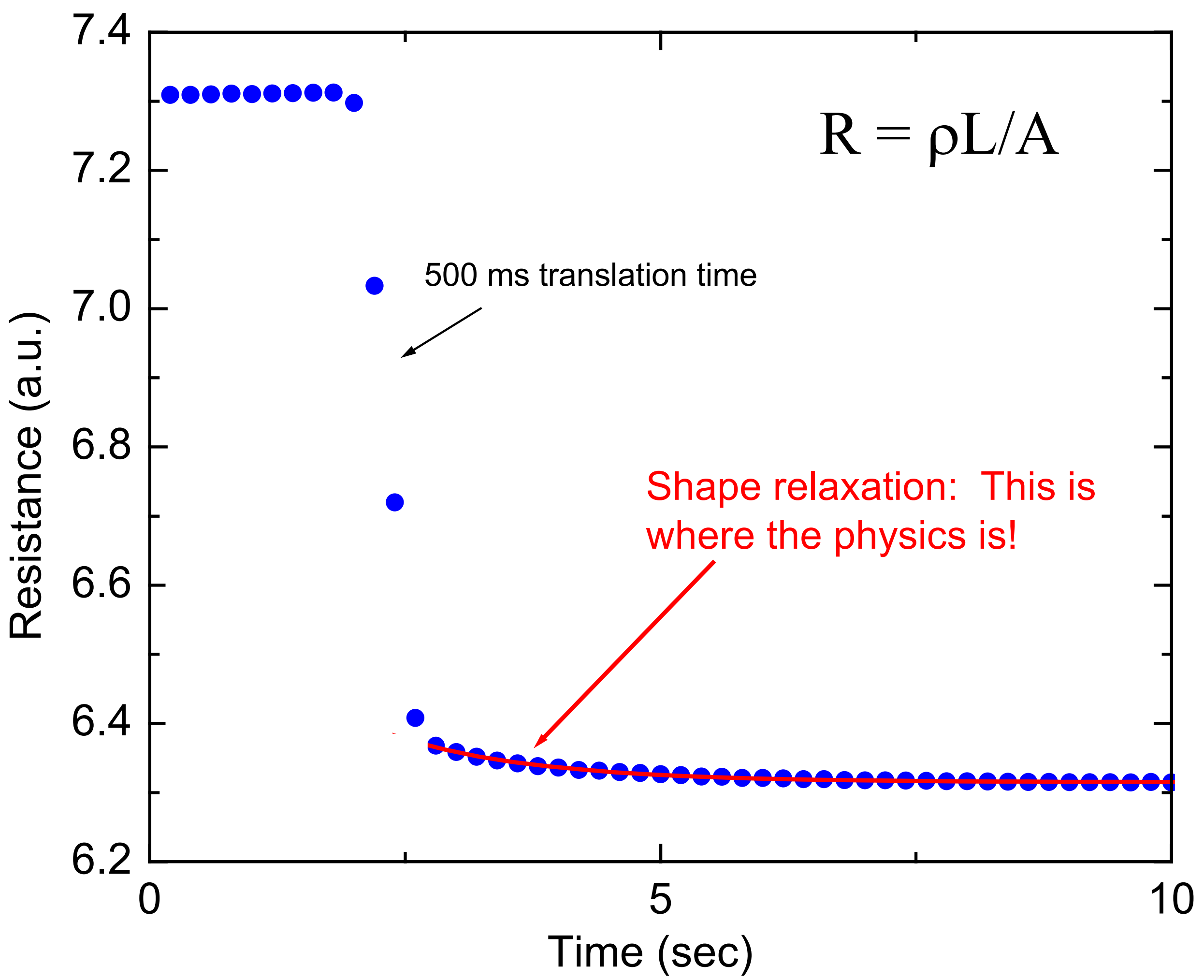
Resistance vs. Time



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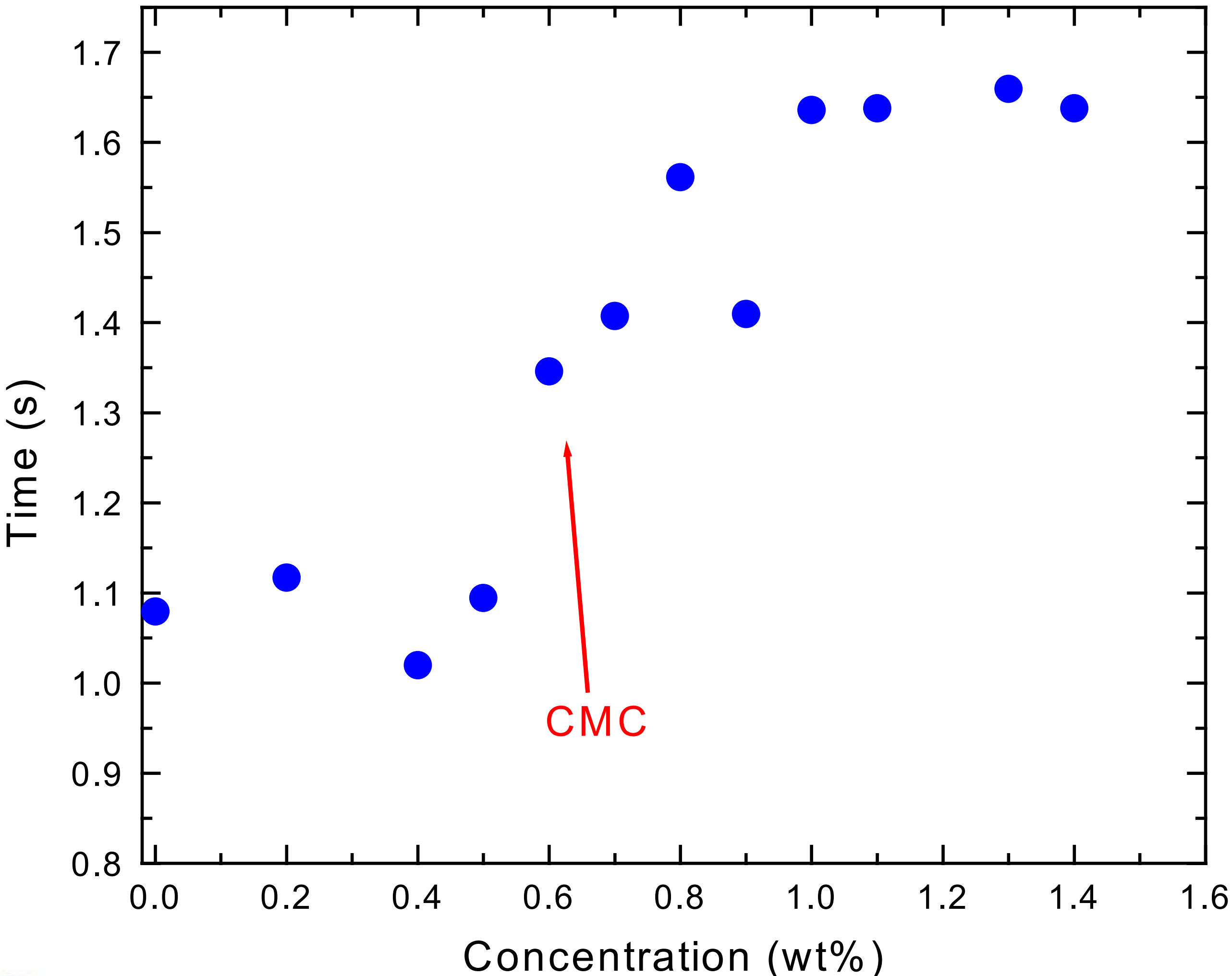
For each concentration we obtain the relaxation time

τ vs. X



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For low concentrations, X < CMC ($\tau \sim 1.1$ s)

- Surface area ***decreases*** on translation of rod. Increased surfactant density at surface ***can*** be accommodated by surface due to its small surface density. There is no need for surfactant to be pushed into bulk.

- Fast capillary waves (> 8 Hz) are induced by the vibration during squishing and result in high electrical resistance. (We measure the envelope decay)

- As capillary waves decay, electrical resistance decreases to final equilibrium value (associated with final equilibrium shape)

So, for small X, we measure the decay of capillary waves, not of surfactant squeeze out

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For large concentrations X > CMC ($\tau \sim 1.7$ s)

- Capillary waves are damped very rapidly for X > CMC, *and do not contribute to measured signal during decay.*

- When rod translates, surface cannot rapidly accommodate the higher surfactant density ➔ surface area is temporarily > equilibrium surface area.

- Surface area relaxes from near equilibrium to equilibrium shape as surfactant is squeezed out from surface. Resistance relaxes with surface topography, where τ is the squeeze-out time of surfactant.

- This is ***not*** a diffusion limited process, which is about four orders of magnitude faster.

Take home message:

Magnetic levitation has numerous applications in studies of fluids, “soft” and “hard” condensed matter physics, and biophysics

1. “Dial in” appropriate gravitational field, e.g., Martian, Lunar
2. The field can be maintained indefinitely
3. Field can be varied with time

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